Sediment acoustics: Wideband model, reflection loss and ambient noise inversion

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Award Number: N00014-06-1-0125
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LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

(1) Consolidation of the BIC08 model of sediment acoustics, its verification in a variety of sediment types, parameter reduction and documentation in preparation for transition. (2) A new model of sediment reflection based on a mixture of models suitable for shallow water sonars. (3) Coupling of BIC08 to rough surface scattering models.

APPROACH

(1) Consolidation of the BIC08 model: This model contains plausible physical processes. It is based on the **Bi**ot-Stoll grain **c**ontact **sq**uirt flow and **s**hear viscous drag (BICSQS) model, which includes squirt flow at the grain-grain contacts [Chotiros, Isakson 2004], combined with improvements in squirt flow modeling, the frame virtual mass extension to account for the random grains rotation [Chotiros, Isakson 2007], and the high-frequency viscous drag correction [Chotiros, Isakson 2008]. The approach is to reconcile common parameters in the different components, and consolidate the input parameters to reduce the parameter count. Further tests are planned to continue to test it against experimental measurements and extend it to a wider variety of ocean sediments, through participation in future shallow-water and sediment acoustics experiments. New experimentation methods are envisioned, including the exploitation of ambient noise for bottom characterization using a compact, partially buried array.

(2) A new model of sediment reflection: This is a new approach to modeling ocean sediments that recognizes that the sediment is often patchy. The reflection measurements from the SAX04 experiment [Isakson, Chotiros, Camin, Piper 2010] are an extreme example. This suggests a new approach to modeling bottom reflection as a random process, in which each bottom bounce contains both a deterministic as well as a random component. This is consistent with recent findings that bottom backscatter is often well described by a mixture of processes [Lyons and Abraham 1999]. It will lead to more realistic bottom models for sonar performance prediction.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Sediment acoustics: Wideband model, reflection loss and ambient noise inversion**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Texas at Austin,Applied Research Laboratories,Austin,TX,78713-8029**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

(3) Coupling of BIC08 to rough surface scattering models: Since the real ocean bottom is rough, it is necessary to be able to combine the BIC08 model with a rough interface, in order to obtain a realistic model of the bottom. For a computationally fast solution, a ray-based approach is likely to be a practical solution, but for accuracy, a finite element approach would be best. This task also includes experimental support equipment to measure seafloor roughness, to allow rough interface scattering models to be tested with at-sea experimental measurements.

WORK COMPLETED

Following the three tasks mentioned in the approach, the work completed may be divided into three corresponding sections:

(1) Consolidation of the new BIC08 model: There are at least two issues to resolve in order to move forward. One is an accurate expression of shear wave speed in a granular medium. Another is the reconciliation of parameter values that are used in different components of the model.

Regarding the expression for shear wave speed, it was shown that the shear wave speed in a granular medium is less than that in an elastic solid of the same shear modulus-to-density ratio. Shear and compressional wave speeds were derived for granular media using a conservation of energy approach. The grains were assumed to be spherical with elastic Hertzian contacts of constant stiffness. The affine approximation was used to determine the relative displacement of grain centers, and it was also assumed that the grains are small compared to a wavelength, consistent with the effective medium approximation. Potential and kinetic energies associated with linear motion were the same as those in an elastic solid, but it was found that shear wave propagation in a granular medium involves additional energies associated with grain rotation. The partition of energies results in a reduction in the shear wave speed, relative to an elastic solid of the same shear modulus-to-density ratio. It was shown that the reduction is an inherent property of granular media, independent of any departure from the affine approximation or fluctuations in coordination number or contact stiffness. The predicted wave speed ratios are consistent with published measurements [Chotiros and Isakson 2010].

Regarding the reconciliation of parameter values, the effort is concentrated about the physics of the fluid film at the grain to grain contact. This fluid film is likely to be very thin, and consequently it may involve new physics related to thin film viscosity. It has been recently found that, for nanometer-scale interfacial separations, the effective viscosity is many orders of magnitude greater than that of bulk water [Goertz, Houston, and Zhu 2007]. Future work will explore the relevance of the new physics of thin film viscosity.

(2) A new model of sediment reflection: The reflection measurements from the SAX04 experiment [Isakson, Chotiros, Camin, Piper 2010] show that the sediment can be highly inhomogeneous. Through-the-sensor measurements of bottom backscattering strength, using the AN/SQS-53C sonar and the SABLE system, as well as similar measurements through the AN/SQQ-32 sonar, have also shown similar patchiness on larger scales. The heterogeneity is on a scale that is likely to be too fine to be properly mapped and may change as a function of time, and therefore it has to be treated statistically. In this approach, the key parameters are the amplitude and the spatial correlation function of the fluctuations.

(3) Coupling of BIC08 to rough surface scattering models: There are some practical issues to be resolved, regarding the spatial sampling of the medium for finite element modeling. In sandy

sediments, the Biot slow wave and the shear wave, which are predicted to have low wave speeds, require very dense meshing of the medium model. A similar problem exists with elastic media with low shear wave speeds. A method to reduce the mesh density is needed before work can continue. It was decided that the work should start with the simpler problem, i.e. the elastic medium with a low shear wave speed. Since a low shear wave speed is usually accompanied by high attenuation, the approach is to model the medium as a fluid surrounded by a thin elastic layer. The thin elastic layer will provide the proper reflection and transmission coefficient and should be thick enough that the shear wave would be completely absorbed before it reaches the fluid core. The compressional wave would pass from the elastic layer into the fluid core with minimal reflection since the impedances are perfectly matched. Similarly, when a wave is transmitted from the fluid core into the elastic layer, there should be minimal shear wave conversion. At the outer boundary, the composite would behave indistinguishably from an elastic solid with a slow shear wave. Tests made with OASES showed that the approach may be feasible.

RESULTS

The results are presented in the same order as the work completed:

(1) Consolidation of the new BIC08 model has made some progress: A key issue is an accurate expression for shear wave speed in a granular medium. The grain motion for shear and compressional waves is illustrated in Fig. 1 (a) and (b), respectively. In both cases, a half cycle including a peak, a null and a trough are shown. At the peak and trough of the shear wave, the grains are displaced from their equilibrium positions. At the null, midway between the peak and trough, the linear velocity, and hence kinetic energy, is at a maximum. In addition, there is a grain rotation, which reaches a maximum at the null. The combination of shear strain and grain rotation produces conflicting shear stresses at the grain-grain contacts and a significant amount of potential energy. The particle motion of a compressional wave is relatively straightforward. There is no average grain rotation. At the maximum linear displacement, the potential energy is also maximum. At the null, the linear particle velocity amplitude and kinetic energy are at maximum, and the grains are compressed.

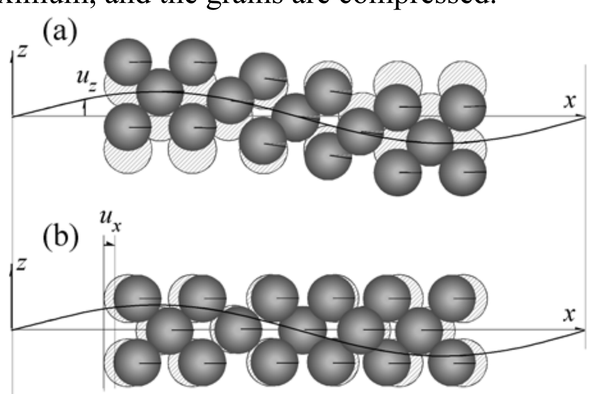

Fig. 1. Illustration of (a) shear and (b) compressional wave motion, particle displacements and rotations at the peaks, zeros, and troughs, in a granular medium with Hertzian contacts. [There are two panels. The top panel illustrates grain motion in response to the passage of a shear wave from left to right. The unperturbed particle positions are shown in the background. It shows shear strain at the extremities of vertical motion, and grain rotation at the null. The bottom panel shows grain motion in the presence of a compressional wave. While there is volumetric strain, there is not average grain rotation.]

The measured ratio of compressional and shear wave speeds in granular media are known to be inconsistent with elastic wave theory, which should be called "pseudo-elastic", since it is an application of elastic wave equations to granular media, whose behavior is often different than that of an elastic solid. The granular medium model developed here solves this inconsistency. As shown in Fig. 2, it is consistent with a large proportion of the published data. The discrepancy with the remaining measurements may be put down to residual moisture, which tends to lubricate the grain contacts, causing slippage. The remaining data points fall between the granular medium and the lubricated grains models (S_t=0).

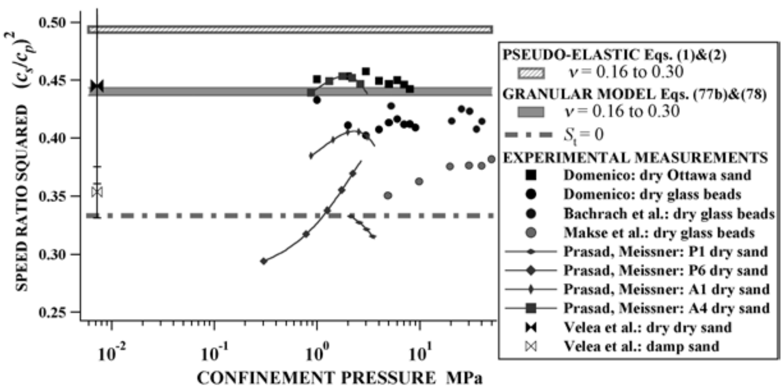

Fig. 2. Comparison of measured and predicted shear-to-compressional squared speed ratios as a function of confinement pressure.
[The plot shows the squared ratio of shear to compressional wave speeds as a function of confinement pressure, from atmospheric pressure to 50 MPa. There are 3 horizontal lines representing the pseudo-elastic, the granular, and lubricated granular medium models. A number of data points, from measurements by Domenico, Bachrach et al., Prasad and Meissner, and Velea et al., are clustered about the granular medium model. The remainder are between this and the lubricated grain model. None are close to the pseudo-elastic model.]

(2) A new model of sediment reflection: The key parameters are the amplitude of the fluctuations and the spatial correlation function of the sediment properties. Measurements of the bathymetry of the SAX04 site by Kraft and de Moustier show that the spatial statistics can be dramatically altered by the passage of a hurricane. Their measurements of bathymetry using multibeam sonars show significant changes in the length scales of the bathymetric variations, from over 10 meters two weeks before the hurricane, to less than 4 meters five weeks after. These values were estimated from the wavenumber spectra of the interface roughness shown in Fig. 14 of Kraft and de Moustier 2010. These findings show that the spatial statistics change significantly with time and weather events.

(3) Coupling of BIC08 to rough surface scattering models: A reduced-mesh model of an elastic medium, with similar properties to water-saturated sand, was tested using OASES. The approach was to replace the elastic medium half-space with a thin elastic layer overlaid on a fluid half-space of the same density and compressional wave speed. To illustrate the problem, the reflection at the water-elastic medium interface was computed at 5 kHz. The reflection loss curves are compared in the right hand panel of Fig. 3. Two layer thicknesses were tried: at 0.06 m, the one-way shear wave attenuation at the bottom of the layer would be 5 dB, and at 0.25 m, 20 dB. The reflection loss curves appear to be indistinguishable. The difference between the half-space model and the layered models are shown in the right panel. The differences are less than 0.06 dB. The region between 0 and the critical angle at 30 degrees is important for shallow water propagation computations. In this region, the 0.06 m layer had

differences of up to 0.003 dB, while the thicker layer gave differences less than ten times smaller. Beyond the critical angle, the differences were larger and showed little correlation with layer thickness, because they are caused by reflection of the compressional wave at the interface between the elastic layer and the fluid half-space. Even though the density and compressional speeds are identical, the difference in shear wave speed causes some reflection of the compressional wave at non-normal angles.

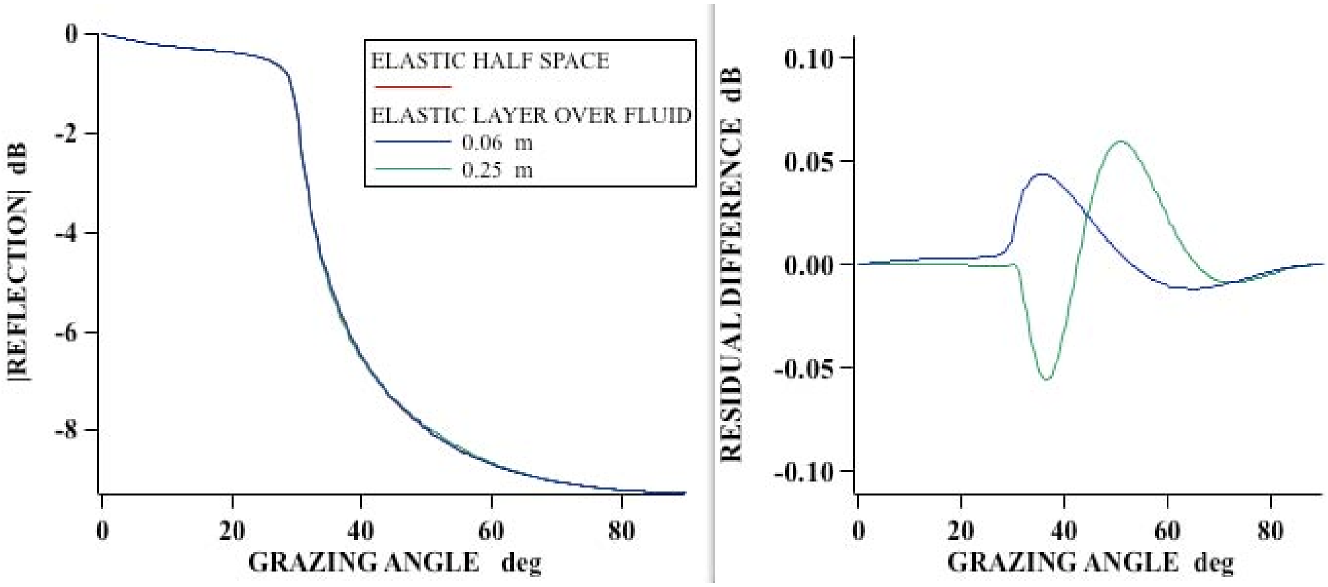

Fig. 3. Comparison of reflection magnitudes at the water-elastic medium interface for an elastic half-space and for composites of an elastic layer over a fluid half space (left) and the differences between the layered models and the elastic half-space (right).
[The left panel shows reflection magnitude in decibels plotted against the grazing angle, for an elastic half-space and elastic layers overlaid on a fluid half-space. The rigth panel shows the difference in dB between the elastic half-space model and the layered models.]

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection and penetration of sound at the ocean bottom are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office. Predictions of sediment wave speeds and attenuations will need to be revised.

TRANSITIONS

Work on sediment variability is being transitioned to the active sonar trainers via the High-Fidelity Active Sonar Training (HiFAST) project. Some aspects of the ocean sediment model, particularly the frequency dependence of sediment attenuation, are being used in the Ocean Bottom Characterization Initiative (OBCI) project.

RELATED PROJECTS

This project is closely related to most projects under the ONR Underwater Acoustics: High Frequency Sediment Acoustics and Shallow Water Thrusts.

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